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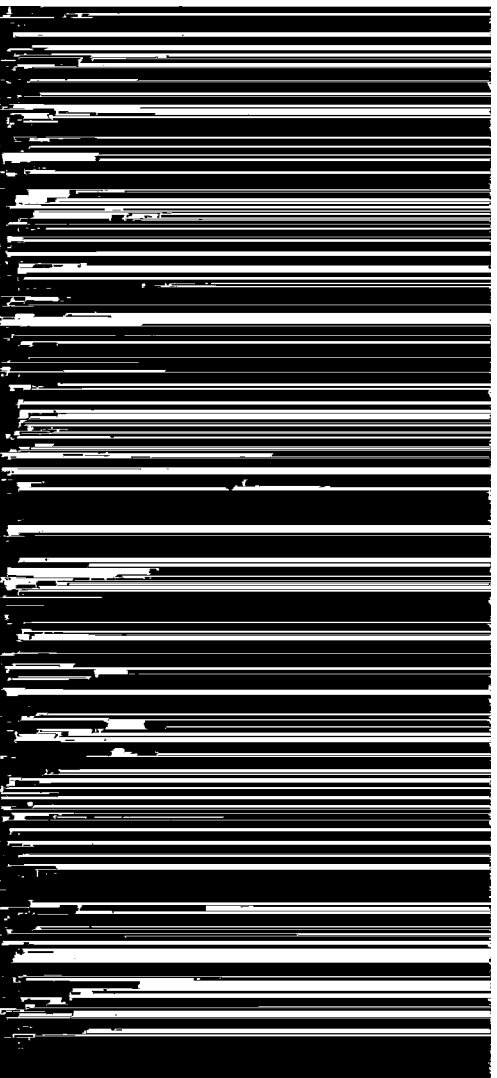
REDUCING SPACE MISSION COST BOOK

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(p. 15, tables
1 & 4, & Fig. 1)

RICHARD CAPUTO AND ROBERT L. STATHI
Jet Propulsion Laboratory, California Institute of Technology

CHAPTER 15 SCIENCE & SOCIETY. Photo Express

ABSTRACT



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Photo is, in a sense our "gateway to the stars". Our first mission offers an opportunity to set a new approach for exploration in the next millennium. So in spite of constraining fiscal resources, our challenge, set by NASA Administrator Mr. Goldin, is to lead the way to low cost exploration of the outer Solar System and beyond.

* Formerly named "Photo First Flyby". At JPL, *preproject* means an activity expected in the future to be a line item in the Federal budget. For the rest of this chapter, we will use the more familiar term *project*.

Background

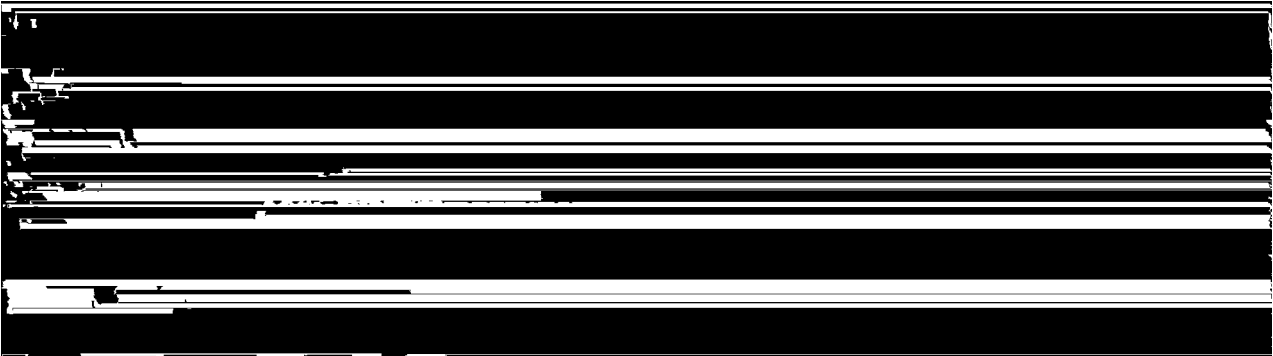
To describe the evolving attempt to keep up with rapidly changing external requirements that has marked the post-Cold War era in NASA supported programs, the approach taken in this chapter starts with a relatively detailed description of the first of the four attempts to come up with a complete system design and project definition. The changing requirements each year will be noted and the new project design/approach described with emphasis on the changes to the previous design/approach.

The Pluto Fast Flyby Project started in early FY92 with the realization that the last known, unvisited planet, could have an initial scientific flyby after a relatively short cruise time of ~6 yrs, compared to Voyager's 12 years to reach the same distance. This could be done by combining a very light flight system (~35 kg) with a powerful launch system (Titan IV/Centaur plus additional upper stages). Such an approach has an annual launch opportunity with a direct trajectory, avoiding the need for gravitational assists from bodies such as Jupiter (with its high radiation field). The impetus for this concept was issuance of the planetary exploration stamp series by the U.S. Postal Service in October 1991. One stamp referred to Pluto as "Not yet explored." Clyde Tombaugh discovered Pluto in 1930 from Lowell Observatory. Before proceeding with this work at JPL, discussions were held with Mr. Tombaugh and in 1992 gave his "permission" to send the first exploratory mission there.

The initial spacecraft concept was largely a single-string design (no redundancy) with an optical camera which would conduct bare minimum imaging, and a radio to perform radio science of the Pluto/Charon system (Salvo, 1993). This initial concept did not yet rigorously consider overall mission reliability, costs, project schedule, or confer with the appropriate scientific group to determine the acceptable science at Pluto/Charon. It was conjectured that two spacecraft could cost <\$200M in FY92 dollars. Based on this initial concept, there was sufficient interest by NASA to start more detailed studies because the general expectation at that time, was that such a mission had a much longer cruise duration (15 to 20 years) and a multi-billion dollar price tag. Pluto is currently in an attractive position just past perihelion and moving away from the Sun in its 248 year orbit. It is thought that Pluto's tenuous atmosphere will condense as it becomes colder sometime early next century (2005 - 2025), after which the opportunity to study its atmosphere will next present itself in about 200 years. Thus, the suggested short cruise time is a key factor in NASA's initial interest. This interest is boosted by the 1989 encounter with Neptune's moon Triton which is a near twin of Pluto in size and present solar distance, and has revealed a complex geology and atmosphere. Finally, some theories of the evolution of the Solar System indicate that there were possibly thousands of planets¹ in the early Solar System and they were nearly all (> 99%) similar to Pluto. Greater knowledge of Pluto would give insight into the dominant forces that shaped our Solar System's evolution (Steen 1992, 1995).^{1,2}

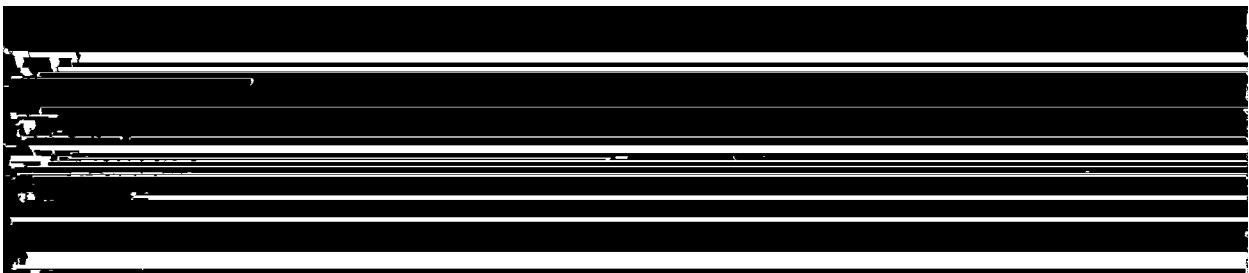
¹S. A. Steen, "The Pluto-Charon System," in G. Burrows, D. Layzer and J. G. Phillips, eds, *The Annual Review of Astronomy and Astrophysics (1992)*, Annual Reviews, Inc., Palo Alto, California, 1992.

²S. A. Steen, "Pluto and the Kuiper Disk," in *Ices in the Solar System* (C. deBergh, M. Festou, and B. Schmitt, eds.), Kluwer, in press, 1995.



detailed specifications of spectral and spatial resolution, signal-to-noise ratio, and coverage for Pluto, Charon, and Pluto's atmosphere. Numerous lower-priority objectives (contained in 1b and 1c) were made optional to avoid driving costs up.

1992 Baseline Mission and Flight System



was followed by a 7.5 year cruise on a direct trajectory to encounter with Pluto in Aug 2005. Earth occultation of both Pluto and its moon Charon was achieved with a velocity of about 16.5 km/sec relative to Pluto.

* In this context, a planet is a body orbiting the sun whose size is sufficient to assume a nearly spherical shape due to gravitational forces.

³Robert L. Stachle, Douglas S. Abraham, John B. Carraway, Paul J. Esposito, Elaine Hansen, Christopher G. Salvo, Richard J. Terrile, Richard A. Wallace, Stacy S. Weinstein, "Exploration of Pluto," paper IAF-92-0558, 43rd Congress of the International Astronautical Federation, Washington, DC, 1992 September.

⁴C. G. Salvo, "Small Spacecraft Conceptual Design for a Pluto Fast Flyby Mission," paper AIAA-93-1003, AIAA/AHS/ASME Aerospace Design Conference, Irvine, California, 1993 February.

TABLE 1 EVOLUTION OF THE PLUTO MISSION

TIME	MISSION NAME	COST OBJECTIVE	CONSTRAINTS	RESULTS/NEW MANDATE
FY92	Pluto Fast Fly-by	FY92\$ 400 M for Mission Development	Launch Quickly	Cost Goal Met Within Constraints
	92 Baseline		Get Data Back from Pluto Quickly	
			Meet Science as Defined	
			by Science Community	Substantial New Technology Injection Mandated
FY93	Pluto Fast Fly-by	FY93\$ 400 M for Mission Development	Introduce Significant Number	Nearly 20 New Technologies Introduced
	93 Baseline		of New Technologies	Mission Development Cost Goal Met
			Rest Same as FY92	
				Life Cycle Cost Need To Be Reduced by 40%
FY94	Pluto Fast Fly-by	Life Cycle Costs About \$550M	Lower Project Funding Profile	Life Cycle Cost Reduced to FY93\$ 580 M
	94 Baseline		Rest Same as FY93	Project Lengthened from 3 1/2 to 4 1/2 yr
				Mission Development Cost To Be Reduced by 40%
FY95	Pluto Express	Mission Development Cost of FY92\$ 400 M	Consider non-radioisotope power sources (RPS);	Scenarios/Approach/Advanced Technology
		incl. Launch System and Possibly Some	Avoid Earth Gravity Assist if RPS is Used; Consider Both	Pathfinder for Low Cost Outer Solar System Exploration
		of Advanced Power System	US and Russian Launch Vehicles; Rest Same as FY 94	

TABLE 2: SCIENCE OBJECTIVES COVERED BY "STRAWMAN" PAYLOAD

Science Objectives	Pluto Express
1a Characterized Global Geology and Morphology Surface Composition Mapping Neutral Atmosphere Composition and Structure	Yes Yes Yes
1b Surface and Atmosphere Time Variability Stereo Imaging High Resolution Terminator Mapping Selected High Resolution Surface Composition Mapping Characterization of Pluto's Ionosphere & Solar Wind Interactions Search for Neutral Species Including: H , H_2 , HCN , C_xH_y , and other Hydrocarbons and Nitriles in Pluto's Upper Atmosphere.	Some Some Yes Yes Partial Yes
Search for Charon's Atmosphere Determination of Bolometric Bond Albedos Surface Temperature Mapping	Yes Yes No
1c Characterization of the Energetic Particle Environment Refinement of the Bulk Parameters (Radii, Masses, Densities) Magnetic Field Search Additional Satellite and Ring Search	No Yes No Yes

Four instruments were proposed to meet the minimum science objectives: a visible camera for surface geology and morphology, an infrared imaging spectrometer for surface composition mapping, an ultraviolet spectrometer for atmospheric composition, and an ultra stable oscillator and signal processor during uplink radio occultation for atmospheric temperature and pressure as a function of altitude. Ambitious goals for the payload comprising all the instruments were established with cost <\$30M (without reserves), mass <7 Kg, and power <6 watts (without contingency). (Note: In July 1991, working prototypes of the most difficult instrument components were completed, giving confidence that these goals could be bettered for flight hardware.)

Several months before closest approach, optical resolution using the spacecraft camera will be better than the Hubble Space Telescope. Within 100,000 km (14 hours before closest approach), imaging pixel size is 1 km on the surface at the sub-spacecraft point. Because the approach is from almost precisely the direction of the Sun, views of the terminator and at middle phase angles are possible for only a few minutes around closest approach. This necessitates a fairly rapid 2.5 second readout rate of the CCD camera detector. With all instruments fixed to the body of the 3-axis stabilized spacecraft, rapid reorientations of the spacecraft are required along with short settling times. In the dim light at 31 AU, the camera optics are sized to provide adequate exposures of about one second (Stehle, *et al.* 199X), ⁵

The flight system approach used two spacecraft, (each designed as a dual string spacecraft with block redundant and cross-strapped components). This is necessary to have a reasonable (> 90%) chance of at least one spacecraft survival after the long cruise. One of the spacecraft would be delayed in flight to arrive at Pluto about 6 months later (with results of the

The 5-yr mission development project is "hardware rich" where key components are breadboarded and brassboarded, and a brass board system of most of the spacecraft is tested. A prototype was planned to be qualification tested and refurbished to serve as a flyable spare. Two identical spacecraft would be built, environmentally tested at the system level to verify integrity.

The spacecraft is three-axis stabilized using cold gas attitude control. While alternative power options (solar, battery, fuel cell, etc.) were left open for further study, a small radioisotope thermoelectric generator (RTG) augmented with capacitors for short peak loads was estimated to be the most cost effective, lowest mass, most reliable approach to a mission at the edge of the Solar System. The needed power 10 years after launch is 63.8 watts electric (including 30% contingency) at 14 volts, and uses standard general purpose heat source modules.

Attitude control uses nitrogen pressurant from the monopropellant hydrazine tank. The attitude control subsystem uses a wide field of view miniature star camera for its inertial sensor. Three solid state rate sensors are used to maintain attitude reference during propulsion maneuvers. Control is through cold gas (N₂) thrusters along all three spacecraft axes. Pointing knowledge is 1.5 mrad, and stability is 10 microrad over one second. Fast slews of 90 degrees require 2.7 minutes (zero rate to zero rate), plus settling time.

A central computer is used for all commanding, sequencing, and computations. The computer uses a 1.5 Mips single-board computer with standard hardware (25 krad), and several candidate processors available. Very Large Scale Integration (VLSI), Application Specific Integrated Circuits (ASIC), and surface mount packaging technology are used for reduced mass. Power strobing is used to minimize power. Direct lines are used

science objectives.

Lower Cost Features in the '92 Baseline

The major factor to reduce costs for the development project was to carry a payload that directly explored only about 25% of the science interests in a planetary flyby. These interests were embodied in the category 1a objectives as defined by the appropriate science working group. This was the minimum that this science group would accept. Without working hard with Outer Planets Science Working Group to arrive at this acceptable minimum, there would have been 3 to 4 times the science objectives and a need for 3 to 4 times the science instrumentation. Thus, scoping the science to was the largest single factor in reducing the complexity, mass, required power and cost of the mission.

It was interesting to note that when the scientific capability of the suite of 4 resulting instruments were examined against all the science interests, they were able to achieve about 75% of the total category 1 science (Table 2).

TABLE 3 RESULTS OF PLUTO MISSION DESIGN and PROJECT DEFINITION

MISSION NAME (year)	RESULTS
Pluto Fast Fly-by '92 Baseline	- Mission Development Cost= FY92\$ 363 M
	- 3 1/2 yr Project Duration (Pre-project is 2 yrs)
	- 7.5 yr Cruise to Pluto
	- 1 yr Data Playback After Encounter
	- Science Is Acceptable Minimum (Category 1a)
	- Global Geology & Morphology
	- Surface Composition Mapping
	- Neutral Atmosphere Composition & Structure
Pluto Fast Fly-by '93 Baseline	- Mission Development Cost = FY93\$ 310 M (\$ 383 M when phase B included)
	- About 20 New Technologies Introduced
	- Flight System Mass Reduced from 165 kg to 119 kg (wet)
	- 8.2 yr Cruise
	- 3 month Data Playback
	- Science Is Acceptable Minimum (Category 1a)
Pluto Fast Fly-by '94 Baseline	- Total NASA Life Cycle Cost Is FY94\$ 620M (reduced from FY93\$ 1100M)
	- Mission Development Cost = FY94\$ 306 M (\$ 340 M when phase B included)
	- 4 1/2 yr Project Duration Due to Funding Profile Limits
	- 9.3 yr Cruise
	- 3 month Data Playback
	- Science Is More Than Acceptable Minimum (Category 1a + Atmospheric Probe)
Pluto Express (FY1995)	- Costs <<'94 Baseline
	- 3+ yr Phase C/D
	- ~10 yr cruise
	- US or Russian Launch Vehicles
	- ~5 JPL People Cruise Mission Staffing
	- Spacecraft Development Approach

TABLE 5 PRINCIPAL TECHNIQUES USED TO MEET PLUTO MISSION REQUIREMENTS

MISSION NAME	PRINCIPAL TECHNIQUES
Pluto Fast Fly-by	- Obtain Science Community Support to Limit Required Science To Highest Priority (Category 1a)
'92 Baseline	- Only 3 Instrument Functions Plus Radio-science Needed to Meet Science Requirements
	- Use Available Technology and in Some Cases, Use Devices Left Over From Previous Missions (e.g., 1.47 m VIKING Antenna)
	- Simple Design (no articulations or deployments, cold gas thrusters, no low gain antenna, etc.)
	- Limit Use of New Technology Only To That With Greatest System Benefit , e.g., solid state power amplifier borrowed
	from commercial parts
	- Use Energetic, USA Launch System (TitanIV/Centaur) With:
	- Known Data Base for Easier National Environmental Policy Act Review Process
	- Shorter Cruise Time
	- Direct Trajectory without Jupiter Fly-by With Minimum Need for Radiation Hardened Parts
Pluto Fast Fly-by	- Maintain Science Community <i>Support</i> for Category 1a Science Objectives and 4 Instrument Functions
'93 Baseline	- Vastly Expand Use of New Technologies (15 to 20 items) With Advanced Technology Program
	- Simple Design
	- Reduce Use of Breadboard/Brassboards
	- No Full System Prototype for Use As Flight Spare
	- Use Test Bed for Flight /Ground Software Development
	- Common Flight/Ground Command Architecture
	- Use Spare RTG from Cassini Project Instead of New Power System Fuel
	- Mission Objectives
	NASA Role (see table 9)
	- New Information System (see table-f O)
	- Improved Project Control (see table 10)
	- Improved Procurement Practice (see table 11)

TABLE 5 PRINCIPAL TECHNIQUES USED TO MEET PLUTO **MISSION** REQUIREMENTS, Continued[illegible]

The next most important factor in **keeping** costs low was **to** keep the rest of the spacecraft simple. For example, there is no instrument scan **platform**, unfolding antennas, or panels that open, Cold gas thrusters are used for attitude control rather than the more complex reaction wheels or moving secondary mirrors. There is **no** low gain antenna.

The third major area for lowering costs in this concept is **minimizing** the use of new technology and utilizing existing **parts** (spares from previous missions), with high inheritance from previous designs and technology. In general, the spacecraft used components that would have been qualified within **2** years (by 1994) with **minor** exceptions. The RTG utilized long mission proven silicon germanium thermocouples, as well as the standard general purpose heat source modules already safety tested for the *Galileo* Jupiter mission. The propulsion subsystem is entirely **off-the-shelf**, with a high gain antenna from **residual Viking** hardware. Many components have *Cassini* mission inheritance. The Solid State Power Amplifier is based on commercially available parts in a new component design. The Telemetry Control Unit is a reduced **function** device using *Cassini* pieces repackaged in a **smaller** form. The exceptions to inheritance hardware are relatively low risk developments.

The use of known U.S. launch systems with a good data base (safety data book developed for *Cassini*) simplifies the launch approval and National Environmental Policy Act review process. This reduces the schedule and cost risk in these areas.

Although not part of the mission **development cost** goal, approaches to mission operations and DSN tracking **were** defined so that the overall project cost would **be** reduced. Prior missions **often** ignored mission operations costs during **early** design phases. A cooperative approach was taken between JPL and a university-based mission operations center patterned in part after the successful JPL/University of Colorado *Solar Mesosphere Explorer* mission. Mission and spacecraft design features are key to lower Mission operations costs such as long periods of unattended operation during cruise, using a single weekly tracking and data collection pass of 4 hours. On-board data processing minimizes the **amount** of engineering data that must be downlinked and analyzed.

Development began on spacecraft capabilities that **allow** cruise commands to be uplinked without elaborate simulation and constraint checking. The encounter **command** sequence is **pre-planned** and tested during cruise and is slightly **adjusted** only immediately **before** closest approach. A large on-board memory permits capture of all **science** data and allows its subsequent return over a limited **downlink** via routine daily DSN passes for up to a year following encounter. A progressive development philosophy was adopted where the basic mission operations system is developed at the start of the project and used **to support** a range of activities evolving from subsystem test, spacecraft test and calibration and into post-launch operations.

The resulting mission development cost of **FY92\$363M** is considerably less than would be expected based on previous experience. For example, even a duplicate set of spacecraft based on the *CRAFT/Cassini* program with a **repetitive** procurement would cost two to three times more. This *Cassini* orbiter spin-off approach to a Pluto Flyby mission would have involved more than a dozen instruments with greater capability, but, would far exceed what the Outer Planets Science

Working Group deemed mandatory for the first Pluto mission. These cost reduction techniques are summarized in Table 5.

FY93 Mission Requirements

At the end of **FY92**, an additional requirement was placed on the mission to introduce substantial new technology into the project, as indicated in Table 1. The rationale was that in addition to the scientific and exploration basis for the mission to Pluto, national interests were also served by accelerating the introduction of new technologies. These technologies would be used in future space missions with some technologies likely to spin-off to commercial uses. In addition, public outreach and student involvement were emphasized as an important aspect of the project.

Substantial amounts of advanced technology are to be introduced without any relaxation of the other requirements such as a mission development cost cap of **FY92\$ 400 million**. This was a severe challenge since introducing numerous new technologies usually increases cost and schedule risk.

The Pluto team responded in early **FY93** by creating an Advanced Technology Insertion activity to transfer new technology to the Pluto project from sources in industry, academia and federally funded research and development centers. The new technologies are also expected to reduce spacecraft mass, thus reducing cruise time and compensating for the lengthening of the development project to introduce new technologies. The '92 baseline is used as a collection of subsystem fall back positions to mitigate increased development risk when necessary.

After establishing a list of potential sources of new hardware and software technology, over 1200 requests for information were sent. After evaluating responses, workshops were held describing the range of project needs for new technology. Finally, after the requested information was evaluated, 16 procurements or agreements were initiated for prototype hardware and software. A NASA research announcement was issued early in 1993 for the purpose of finding and demonstrating promising instrument technologies. As result of these initiatives, key technologies listed in Table 6 emerged as applicable to the Pluto project (Stachle, *et al.* 1993).⁶

One of the key indicators of improved performance is reduced subsystem mass. If the launch system is the same, this translates into reduced cruise time to Pluto for direct trajectories. The '92 baseline spacecraft mass (including payload) went from 165 kg to 119 kg in the '93 baseline. The greatest improvements were in the telecommunications and propulsion subsystems, with significant improvements possible in structure and electric power.

The project schedule was translated one year from the '92 baseline, and the project start was set for FY96 with a 3.5 year phase C/D and a dual launch in Jan/Feb '99. The estimated cost for mission development (project start to launch + 30d) is **FY93\$ 322 million**. Because of the large

⁶Robert L. Stachle, Stephen Brewster, Doug Caldwell, John Carraway, Elaine Hansen, Paul Henry, Marty Herman, Glen Kissel, Shirley Peak, Chris Salvo, Leon Strand, Richard Terrile, Mark Underwood, Beth Wahl, and Stacy Weinstein, "Pluto Mission Progress Report: Lower Mass and Flight Time Through Advanced Technology Insertion." *44th Congress of the International Astronautical Federation, Graz, Austria, October 16-22, 1993.*

number of new technologies, substantial funding was needed prior to project start. When FY95 (Phase B) is added, the total is **FY93\$383** million which is essentially the same as estimated at the end of FY92. The '93 Baseline cost breakdown for the phases B+ **C/D** is shown in Table 4.

To keep the cost less than the cap of **FY92\$ 400** million while substantially increasing the use of new technology, project risk was increased by dropping the building and system testing of a flight prototype system. Hardware development would go directly from engineering model at the assembly level, to flight units. In addition to staying within the cost cap, the mission objective to launch as soon as practical (5+ years for phases A, B and **C/D**) was maintained. This required a large increase in **funding** after the first year, and the phase B budget was **FY93\$ 61** million to accelerate the phase B work so that it could be done in one year. Estimated total NASA life cycle cost of the project from phase B to encounter at Pluto plus 1 year for data analysis including the launch system and mission operations for 10 years, was **FY93\$1, 100** million.

PLUTO MISSION

TABLE 6: KEY ADVANCED TECHNOLOGIES

SYSTEM	FY92	ATI GOAL	FY93	TECHNOLOGY •
Spacecraft System				electronic packaging MMIC, MCM, ASIC
Telecommunication	25.2 kg	16.8 kg	12.75 kg	micro-packaged digital receiver (MMIC, MCM) composite structure high gain
Mission Operations and Data Analysis	\$TBD	¹	² \$150 M	concurrent test bed development of flight & ground systems common flight & ground command architecture/language
	29.5	20.1	31.3	
				(FY92: & ATI Goal: 350 ÆV m/s, FY93: 130 ÆV m/s)

The baseline launch system was still the Titan IV-Centaur plus Star 48 and Star 27 solid upper stages. The cruise time to Pluto is 8.2 years and one spacecraft is delayed one year during cruise to allow adjustment of the second encounter based on the results of the first encounter.

Figure 1 shows a layout of the '93 baseline flight system design with the improvements over the '92 baseline. Table 6 shows the resulting system mass representing a reduction of about 28% (nearly 50 kg). The four instruments (visible camera, infrared imaging spectrometer, and ultraviolet spectrometer, and the ultra stable oscillator for the radio receiver) were the same as in the '92 baseline. The basic flight system approach still used two identical spacecraft, each dust string with block redundant and cross-strapped components to have acceptable reliability y after the long cruise to Pluto.

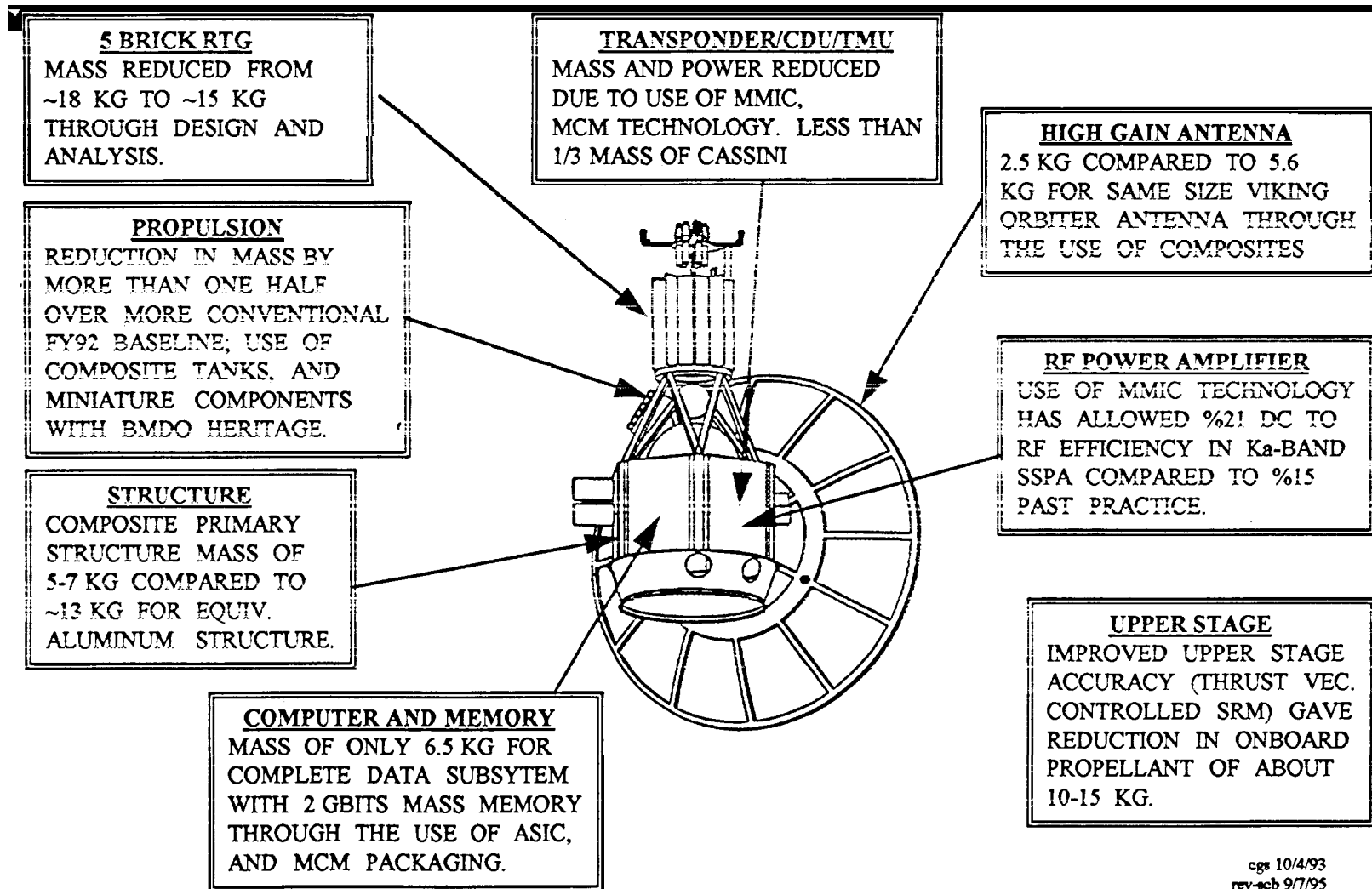
The introduction of new technology into the telecommunications subsystem allowed the use of a lighter composite structure antenna, high density electronics packaging, and higher efficiency RF amplifiers. The mass of this subsystem was reduced in half to about 13 kg, and only used 22 W while transmitting. The key to reducing the transponder mass was using advanced monolithic microwave integrated circuit and multi-chip module packaging technologies. The use of an all-digital receiver (12 W Pluto versus 15 W best practice), and the increase DC to radio frequency conversion efficiency (21 % Pluto versus 15% best practice), reduced the overall power requirement and reduced power system cost. Use of the 70 m ground antenna quadrupled the downlink data rate to 160 bps from the 1.5 m high gain antenna on the spacecraft using X-band (8GHz). Use of advanced electronics packaging in the spacecraft computer increased the science data storage volume from 400 Mbits to 2 Gbits while slightly reducing mass and staying within the power goal of 6 W.

The '92 baseline design had a mass of 2.7 kg for the attitude control subsystem based on a star tracker camera weighing less than 0.5kg and featherweight valves, regulators and milliNewton thrusters. As a reserve against the possibility that a micro star camera could prove inadequate or difficult to qualify for the Pluto mission, the mass

Figure I

PLUTO '93 BASELINE DESIGN

THERE ARE MANY IMPROVEMENTS OVER THE FY 92 BASELINE



Propulsion subsystem mass went from 20 to 10 kg based on use of miniaturized pressure regulators and valves, a composite over-rapped pressurant/propellant tank, and a surface tension propellant management device. Mass of the hydrazine monopropellant was reduced from 24.6 to 7 kg with improvements in the injection accuracy by using 3-axis stabilization of the upper stages plus reduction of the overall spacecraft mass. The '92 design using all aluminum structure was changed to a mix of aluminum and graphite-epoxy composite, and the cabling and connectors mass were minimized to reduce structure and cabling subsystem mass from 20 to 14.6 kg. Improved thermal zoning with the RTG eliminated the need for small, separate radioisotope heater units and for controllable electrical heaters in the thermal subsystem, Central power conversion with several voltages available was enabled by small size and short cable runs.

Advanced power conversion technologies such as *alkali metal thermoelectric converters* and *thermophotovoltaic* converters were considered with the potential to significantly reduce the mass of the power subsystem. However, both of these technologies were felt to be too immature to meet the Pluto mission's schedule requirements (FY99 launch). A change in the RTG's support structure did allow a mass reduction from 23.2 to 19.4 kg for the '93 baseline.

Lower Cost Features in the '93 Baseline

The introduction of these advanced technologies did reduce the mass by nearly 50 kg. This in turn reduced mission operations costs on the direct trajectory because the launch system could impart a higher Earth escape velocity.

For the baseline RTG power source option, a plan was devised to use the spare fuel elements from the *Cassini* RTG rather than new fuel, and this reduced cost substantially. Although the nuclear fuel was aged and generated less heat than new fuel, a small RTG could be built with sufficient power by using 6 of the general purpose heat source modules. Two flight units and a fueled spare were possible at a cost savings of about \$25 million (the *Cassini* spare has 18 modules).

The approach to mission operations was modified somewhat by using a combined team at JPL (operations at critical times or for anomalous events) and a university team (many routine operations at a remote site using students and professionals). Eight hours of tracking and data collection per week are planned.

The full-up prototype system (which acted as a flight spare spacecraft) was dropped as a significant cost saving item, increasing the risk of successfully completing the project within schedule and budget. A number of compensating risk reduction and cost saving features were introduced into the '93 baseline project in a wide range of areas such as: teaming and organization (Table 7), design approach (Table 8), NASA role (Table 9), information system and project control (Table 10), and the procurement approach (Table 11). All these cost reduction techniques used in the '93 Baseline Pluto Mission are summarized in Table 5.

The approach used for teaming and project organization have a great deal to do with the people productivity in executing a project. Although technology receives most of the emphasis in

describing cost reduction, the people system in place to implement the project is a powerful cost driver. Table 7 summarizes a host of organizational changes to increase the people effectiveness for the Pluto project. It is difficult to quantify the cost reduction of each of these suggested changes, and it is almost impossible to estimate the combined effect. They are part and parcel of a basic re-engineering of the way projects are done at JPL.

The thrust of these 18 changes to the way projects are executed at JPL is to change the focus away from using the institutional structure that evolved over the years. This is primarily a skill-based matrix organization that, at one time, reflected the way a project was organized. There is emphasis on serving the institutional organization needs rather than the project needs. To the extent that these two spheres are completely overlapping, you have a effective alignment of the institution and the projects it generates. As shown in Table 7, a change to more directly support projects is needed. Whatever the changes are called (soft projectization, re-engineering, etc.), they need to achieve the result of focusing the talent and energies of the

FY94 Mission Requirements

The '93 Baseline Pluto Mission met or exceeded all the NASA requirements levied on the mission including development cost and substantial new technology. The FY92\$ 369 million cost for mission development (phases B + C/D) was part of the life-cycle cost of FY93\$ 1100 million (total cost to NASA) which also includes the launch system and mission operations to 1 year after Pluto encounter. At the end of FY93, the emphasis and frame of reference changed from the mission development cost at JPL to the total NASA life cycle cost for the entire mission. An additional cost requirement was placed on the mission and it is that the life cycle costs be about half the FY93\$ 1100 million as indicated in Table 1.

In addition, the funding profile prior to project start (phases A and B) was constrained to be less than the optimum needed to develop the new technologies and to implement the project quickly at lowest overall cost. All other previous requirements such as substantial new technology, early launch, short trip time, public outreach and student involvement were maintained.

The primary response to these new requirements was to go through an extensive mission redesign effort which primarily considered new launch systems and new power subsystems while examining new spacecraft design approaches and mission operations scenarios. The results of this effort are embodied in the '94 Baseline project and mission design. The overall technical approach and most aspects of the project approach and cost estimate were reviewed by the 1994 Technology Challenge Team. Many review board members were from small, quick, low cost projects such as Navy Research lab's *Clementine* project (see case study in chapter?) and Johns Hopkins Applied Physics Lab *NEAR* project (see case study in chapter ?), and there was strong endorsement of the technical and programmatic approach identified in the '94 Pluto baseline.

To substantially reduce NASA life-cycle cost, the proposed baseline launch

Table 7 New Approach to Teaming and Organizational Factors
Used in '93 Baseline

Skunk Works™-style colocated team involved for the duration of the project

mixed team with young and senior experienced who are open to new approaches

interdisciplinary team with full range of skills needed to conceptualize the mission and bring the project home, i.e., mix team with creative and innovative types, and those who can follow through and prefer more detailed work

- workforce cap with team members either near full time or small fractional time as-needed consultants

flat rather than hierarchical organizational structure

team members accountable as individuals (not line organization) and responsible for WBS deliverables, reliability, and cost through

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restructure WBS so the mission operations **development** and ground **data** system development are redefined in the same **system WBS element** as the flight **command** and control system.

- groupware to allow on-line, up-to-date **information** and file sharing, with information modules maintained by person responsible for WBS element.

all project meetings available by telecomm or in person

TM Skunk Works trademark property of Lockheed Advanced Development Co.

Table 8 New Flight System **Design** Approach

- concurrent design of all systems while keeping **track** of life-cycle cost, mass, power, performance, and schedule
- concurrent development from day **one** with persons responsible for **all** major **WBS** deliverables involved
- integration of the design and implementation of the **system** software of the flight and the ground data systems, and their incorporation within a single. end-to-end information system
- use of breadboard for Advanced Technology **Insertion** technology, and brass board hardware for almost **all** subsystems, and system **t**esting of the brass board equipment
- establish length of development **schedule** and don't change. it
- use common high order language **and** same operating system **rind** S/W in ground tests as in flight operations, and onboard RISC processor
- simplified approaches to flight operations, **to** the role of requirements in design, and the approach to project documentation
- basing reliability on **Class C mission** approach with **some** tailoring for critical items
- spares limited to assembly level (integrate.d) items with procurement time greater than 6 weeks
- eliminating radioisotope heat **ing** units by using RTG via a thermal **zone** configuration design*

* This applies to the baseline concept only. Other power source options might necessitate the use of RHUs. A final decision on the power source will not occur until **after** completion of mission options tradeoffs during Phase. **A/B**.

Table 9 Supportive NASA Role

- early decision on key project components that drive launch approval/National Environmental Policy Act compliance work such as new project start dates, launch dates, etc.
- early interagency agreement on production process for environmental impact statement launch system safety data book, and safety analysis report generation
- timely release of notice of intent by NASA as part of the environmental impact statement process
- timely direction by NASA in launch vehicle choice
- more substantial early budgets to make investments required to reduce life cycle costs

Table 10 Improved Information System and Project Control Used in '93 Baseline

- simplified; flexible drawing and drawing release system
- thoroughly record important work
- requirements documents less than 1 page
- no written document generated until a user requests it
- no document generated unless team carrying out project needs particular document
- document a new design by as-built (earlier generation plus changes/deltas)
- use a risk management approach throughout the mission development that includes risk identification, risk tracking and risk mitigation strategies for technical, cost, schedule and programmatic risks
- establish reserves and allocate via plan for cost, schedule and flight system design margins
- use of integrated schedules and a simplified earned value system with frequent statusing to maintain better control of the project
- low disruption potential planning with pessimistic (low budget) approach to detailed planning for next fiscal year

Table 11 Improved Procurement Approach Used in '93 Baseline

- establish **specifications/requirements** prior to contracting
- **make/buy** decisions based on cost and most qualified source
- buy hardware and **software**, not designs and studies
- set **difficult** specifications where they count (to achieve cost, mass, power usage goals) and relax elsewhere
- implement cost cap contracts
 - communicate importance of cost performance to contractor **CEOs**
 - no contract mods without primary **accountable** team member approval (the primary accountable is the technical lead reporting to the project manager)
- minimum RFP agenda
- streamline University contracting, i. e. two page cent rack plus cover letter
- use contractor procedures
 - reporting format
 - product assurance
 - delegate contractor responsibility to get good vendor bids for subcontract work
- use frequent informal cost and **schedule** status discussions between **JPL** and contractor cognizant individuals
- use simple contract cost and **schedule** monitoring and management tools
- solicit contractor ideas on:
 - commercial applications
 - competitiveness
 - educational benefits
 - ways for government to **amplify** benefits
- contract for current item with **option** to produce next step in development
- include contractors in project team and avoid adversarial relationships to improve communications, avoid **misunderstanding** and reduce costs
- provide contractor with timely funding unless agreed otherwise
- implement "just in time" approach

increased to a total of 6.5 years, with Phase C/n at 4.5 years. A dual launch was scheduled for Jan/Feb '01 with direct trajectories to Pluto.

The estimated cost for mission development (project start to launch -130d) to deliver the flight systems is FY94\$ 306 million including a 30% reserves held at JF'1.. When FY96 (phase B) is added, the total is FY94\$ 340 million which is 15% less than the '93 baseline cost estimate, and 30% lower than the original FY92\$ 400 M phase C/D cost cap.

To lower the mission development cost while maintaining the introduction of new technology, and stretching the project to accommodate a lower budget profile, risk is increased by dropping the building of brass board models. The technology development sequence defined was to go from breadboard to engineering model before building flight equipment (brassboard models are to be built by exception only).

To compensate for this increased risk, several modifications were made to technical implementation. Two of the more important modifications are: design-to-cost techniques that are supported by the Project Design Center (PDC) which allows quick subsystem and system trades to be made simultaneously considering, technical and cost factors; and a Flight System Testbed (FST)

The most substantial change in the technical approach is the baselining of Protons with PAM-D and Star 27 solid upper stages for the launch system. The cruise time to Pluto is 9.3 years, with one spacecraft delayed 6 months during cruise to allow for feedback from the first encounter. The spacecraft design is intended to accommodate the backup launch system, a Delta 11 (7925) which uses an Earth-Jupiter gravity assist trajectory with a Nov '01 launch. The cruise duration using the backup Delta with gravity assist is 13.3 years, with initial encounter with Pluto/Charon in early 2015. Shorter flight times are possible with a closer approach to Jupiter, and the associated higher radiation dose.

The '94 system dry mass is 158 kg including 26 kg of contingency and 15 kg for the drop zond and associated equipment. The wet mass is 182 kg. This is an increase of 63 kg over the '93 baseline design due primarily to the drop zond and changes to the launch system.

The four instruments were the same as in the '93 baseline, but a science data processor was added which is a clone of the S/C data computer.

As with the prior baselines, the flight system approach uses two spacecraft with each designed as a dual string spacecraft with a combination of block redundant and cross-strapped components to be able to have acceptable reliability after the long cruise to Pluto.

Lower Cost Features in the '94 Baseline.

A summary of the techniques used to meet mission requirements is shown in Table 5. The single largest cost reduction factor is utilizing the Proton rather than the Titan IV to reduce launch system costs. Also, to save upper stage costs, a spin stabilized stack is used instead of a

Table 12 Design/Technology Factors in Reducing '94 Baseline Costs

Telecommunications Area:

- double the downlink data rate by increasing the antenna diameter from 1.5 to 2 m, and increase the transmitter power from 3 W to 5 W

increased X-Band antenna gain by 15% using center fed approach without increasing cost or mass

included "hooks" for a Ka-Band downlink to increase robustness of design if 70 m stations of DSN are unavailable (Ka-Band Solid State Power Amplifier must be provided from funding sources outside the project based on multi-mission value)

incorporated radio science into digital receiver to reduce mass and power of the radio science hardware without affecting communications

- joint development and flight buys of the transponder with the Mars Surveyor Program to save cost to each program

Power/Pyro Area:

- the use of centralized power

Table 13 Other Factors Used to Reduce '94 Baseline Costs

- Use 70 meter antenna as much as possible for encounter data downlink to reduce transmission time by factor of 4 compared to 30 meter antenna
 - Have clear interface with science instruments with limits on amount of data return
 - design flight system for mission operations (MO) to reduce/eliminate uncertainty in MO requirements
- use "beacon cruise" operations
- listen versus track for 3-bit health status
 - listen as opportunity permits
 - track-at-will at non-DSN sites
- combine JPL with University for multi-center ops to best

Table 13 Other Factors Used to Reduce. '94 Baseline Costs, continued

FY95 Pluto Express

The FY94 Pluto Fast Flyby approach still did not meet NASA's needs for advanced technology and total cost. In the meantime, the New Millennium Program was begun to develop advanced technology for Pluto and a variety of other space science missions, making it possible to offload some technology development budget. With New Millennium, Mars and other missions becoming reality, there became more missions with which Pluto could share. NASA supported the proposed "sciencecraft" approach to mission development, where instead of soliciting individual scientific instruments rather much of the spacecraft design has been cast, an integrated set of investigations from a single team will be solicited early in Phase A. This science group and members of the engineering team will re-forge into an integrated implementation team responsible for end-to-end mission design and implementation. Operations, encounter design, and instrumentation are all considered together as starting points, from which technology selection, flight system design, software and all the other needed elements for an end-to-end mission success will emerge as driven by cost and technology pathfinder considerations.

With recent discovery and detection of numerous objects in the Kuiper Disk (e.g., Cochran, *et al.* 1995),⁷ encounter with at least one of these objects is now anticipated as part of an extended mission. No additional development cost is incurred to allow this, though operations beyond Pluto will incur some expenditure,

The result of these and other advancements, and the leverage now possible from other programs, is Pluto Express, which can be performed for a fraction of the cost of the FY94 baseline. Actual cost depends on launch vehicle selection, trajectory and launch year choice, and new start date. Pluto Express affords NASA maximum programmatic flexibility to help obtain a new start in the turbulent fiscal environment. One possible sciencecraft configuration is shown in Figure 2. Using an advanced radioisotope power source, flat antenna, integrated microelectronics, and other innovations, sciencecraft dry mass is an estimated 75 kg. Using beacon cruise, where onboard software determines when the spacecraft needs to communicate with the ground, cruise mission operations employs about 5 people at JPL, dropping total operations phase costs substantially. All other previous requirements such as substantial new technology, early launch, short trip time, public outreach and student involvement are maintained. Costs are estimated for different leading options, but, they are not reviewed adequately to be included in this reference work.. However, the mission as presently conceived

2. Concurrent Design/Cost; The usual approach is to design to meet technical requirements and then check the cost to see how the design team did against the cost requirement. Design-to-cost tools are being developed so that the cost dimension is understood and applied to any design dimension during the incremental process of coming up with a

real time cost actuals. The combination will allow a better planned and executed project at lower overall cost and risk.

6. Close Alignment with the New Millennium Technology Development and Demonstration Program: Pluto Express and the New Millennium Program are closely linked, with key staff dual appointments, and frequent, informal coordination among many other team members. New Millennium will develop and flight demonstrate many of the key technologies needed for Pluto Express. Not only will Pluto Express use the demonstrated technologies, but will attempt to use the actual devices without change in design through exercising a next-unit purchase option in the contracts opened by New Millennium. In some areas, this will allow Pluto Express to eliminate most development costs and to obtain flight units at recurring costs. In addition, to reduce the cost of the mission operations (phase F), a significant amount of flight system automation will be developed in New Millennium and utilized by Pluto Express.

It is expected at this time that the Pluto team will meet the current set of requirements for this mission to the edge of the Solar System. In today's tumultuous fiscal environment, it is not clear how the requirements will continue to evolve and whether Pluto will remain "not yet explored" for the foreseeable future.

References

[see footnotes]

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